

OBSERVATIONS OF 20 MILLISECOND PULSARS IN 47 TUCANAE AT 20 CM

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ABSTRACT

We have used a new observing system on the Parkes radio telescope to carry out a series of pulsar observations of the globular cluster 47 Tucanae at 20-cm wavelength. We detected all 11 previously known pulsars, and have discovered nine others, all of which are millisecond pulsars in binary systems. We have searched the data for relatively short orbital period systems, and found one pulsar with an orbital period of 96 min, the shortest of any known radio pulsar.

The increased rate of detections with the new system resulted in improved estimates of the flux density of the previously known pulsars, determination of the orbital parameters of one of them, and a coherent timing solution for another one. Five of the pulsars now known in 47 Tucanae have orbital periods of a few hours and implied companion masses of only $\sim 0.03 M_{\odot}$. Two of these are eclipsed at some orbital phases, while three are seen at all phases at 20 cm but not always at lower frequencies. Four and possibly six of the other binary systems have longer orbital periods and companion masses $\sim 0.2 M_{\odot}$, with at least two of them having relatively large orbital eccentricities. All 20 pulsars have rotation periods in the range 2–8 ms.

Subject headings: binaries: eclipsing — binaries: general — globular clusters: individual (47 Tucanae) — pulsars: general

1. INTRODUCTION

Soon after the discovery of the first millisecond pulsar (Backer et al. 1982), Alpar et al. (1982) proposed that low-mass X-ray binaries (LMXBs) are the progenitors of millisecond pulsars. Given the high incidence of LMXBs in globular clusters, searching for millisecond pulsars in clusters became a natural goal. After much effort, the first such object was discovered, an isolated pulsar with a period of 3 ms in M28 (Lyne et al. 1987). Following searches of many clusters in the late 1980s and early 1990s, over 30 pulsars are now known in 13 clusters. In contrast to most pulsars in the Galactic disk, the majority of cluster pulsars have short rotation periods and are often members of binary systems (see Kulkarni & Anderson 1996 for a review).

Searches for millisecond pulsars in globular clusters encounter two main difficulties. Firstly, since globular clusters are on average more distant than the ~ 2 kpc within which most large-area surveys have been sensitive to millisecond pulsars (see, e.g., Camilo, Nice, & Taylor 1996), much longer observation times are typically required than for Galactic searches. This in turn increases the complexity of the data-reduction task. Such observation times are feasible only because of the small number of search targets. Secondly, for binary pulsars there is the added difficulty that the apparent pulse period may change significantly as the pulsar experiences orbital accelerations during the longer integration. If this issue is not addressed at the data reduction stage — and with significant exceptions (Anderson et al. 1990) it rarely is, because of the massive computational requirements — many relatively bright binary pulsars

may remain undetected.

Despite these difficulties, the rewards of a thorough search can be significant. Because of the high probability of close stellar interactions, unusual binary systems not otherwise expected in the Galactic disk may form in clusters. In addition, for clusters where several pulsars are found and studied with the detail allowed by high-precision timing measurements, much can be learned about the clusters themselves. Applications to date include a determination of the core mass distribution from measurements of pulsar accelerations and positions, and limits on intra-cluster medium properties, by measuring the dispersion of various pulsars (Phinney 1992; Anderson 1992).

The basic observed and derived properties of 47 Tucanae (NGC 104) used throughout this paper are summarized in Table 1. The fact that it is a relatively nearby cluster with a high stellar density makes it an attractive target for pulsar searches. 47 Tuc together with M15 have been by far the most prolific cluster targets for pulsar searches to date, with surveys revealing 11 and eight pulsars respectively (Manchester et al. 1991; Robinson et al. 1995; Anderson 1992). The observed population of pulsars in these two clusters is very different: while those in 47 Tuc are all millisecond pulsars, the pulsars in M15 are more varied in their properties, including slowly-spinning pulsars and a rare double neutron-star binary (Prince et al. 1991). It is also worth noting that although all pulsars in M15 have had positions and period derivatives determined using pulsar timing techniques, this has been possible to date for only two of the pulsars in 47 Tuc. This is due mainly to the different

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TABLE 1
OBSERVED AND DERIVED PROPERTIES OF 47 TUCANAE.

Parameter	Value	Reference
Center R.A., $\alpha_{47 \text{ Tuc}}$ (J2000)	00 ^h 24 ^m 05 ^s .9	Guhathakurta et al. 1992
Center Decl., $\delta_{47 \text{ Tuc}}$ (J2000)	-72° 04' 51."1	Guhathakurta et al. 1992
Distance	4.6 kpc	Webbink 1985
Central mass density, $\rho(0)$..	$4 \times 10^5 \text{ M}_\odot \text{ pc}^{-3}$	This work*
Angular tidal radius [†]	40' (54 pc)	Da Costa 1979
Angular core radius [‡]	12."2 (0.27 pc)	De Marchi et al. 1996
Escape velocity	56.8 km s ⁻¹	Webbink 1985
Velocity dispersion	13.2 km s ⁻¹	Webbink 1985

*The value quoted is a revision of Webbink's (1985) catalog entry (see §5.5 for details).

†Also known as the "limiting radius", this is the radius at which the King model surface brightness-radius profile drops to zero (King 1962).

‡The core radius is a scale factor used in the King model, and denotes the radius at which the number density of stars in the cluster per unit area is half the central value.

telescopes used and different interstellar scintillation characteristics: at Arecibo, Puerto Rico, the majority of the distant pulsars in M15, whose apparent fluxes vary little, are detectable on most days, while at Parkes, Australia, most pulsars in 47 Tuc are visible only when the interstellar weather is propitious and the pulsar signals are amplified in the observing radio band by scintillation. Unfortunately this has meant that many of the scientific objectives suggested by the wealth of pulsars known in 47 Tuc remain unfulfilled.

In mid-1997 a new, sensitive system for observing pulsars at a wavelength of 20 cm became available at the Parkes telescope. Pulsars are in general steep-spectrum sources (Lorimer et al. 1995), and all pulsars in 47 Tuc were discovered at a wavelength of 50 or 70 cm (Manchester et al. 1990, 1991; Robinson et al. 1995). However, the new system provided such performance improvements that observations to study the known pulsars and to find previously undetected pulsars seemed desirable. These observations were so successful in the rate of detection of previously known pulsars and with discovery of new ones, that we have moved to observing the cluster almost exclusively with the new system. In this paper we report on the discovery of nine binary millisecond pulsars in 47 Tuc and give improved parameters for some of the previously known pulsars.

In §2 we describe the observing system used, list the observations made, and outline the data reduction carried out. In §3 we estimate the sensitivity of the survey for isolated and long orbital period pulsars, and compare it to that of past surveys of 47 Tuc. In §4 we summarize the results, including parameters for the newly discovered pulsars and updated parameters for some previously known systems. Finally, in §5, we discuss some limitations, and implications, of our survey and its results.

2. OBSERVATIONS AND DATA ANALYSIS

Since 1997 October we have been using the Parkes telescope together with the pulsar multibeam data-acquisition system to observe the globular cluster 47 Tuc at a central radio frequency of 1374 MHz. The system consists of a cooled, dual linear polarization, 13-beam receiver package (Staveley-Smith et al. 1996), and new filter banks, single-bit digitizer, and data-acquisition computer.

Each of the 13 beams has a half-power diameter of about 14' on the sky. Since a single beam encompasses the great majority

of the cluster stars (cf. Table 1), we record data from the central beam only (but see discussion in §5.1.2), while pointing the telescope at 47 Tuc C, the first pulsar discovered in this cluster. Total-power signals from each of 96 contiguous frequency channels, each 3 MHz wide, are one-bit sampled every 125 μ s and, together with relevant telescope information, are written to magnetic tape for off-line processing. Data are usually collected on days when a pulsar survey of the Galactic plane is also underway (Lyne et al. 2000), and are recorded from 47 Tuc for up to five hours daily. Table 2 contains a log of all observations reported in this paper.

The largest continuous data sets recorded are 4.66 h long, corresponding to 2^{27} time samples. With the computing resources presently at our disposal, it is impracticable to reduce such data sets in single, coherent, Fourier analyses. Furthermore, since about one third of the pulsars already known in 47 Tuc are in binary systems, some with orbital periods of under 3 h (Robinson et al. 1995), we would select against such systems if we analyzed each large data set as a whole. As a compromise between computational feasibility and sensitivity (both to weak radio sources and relatively short-period binaries), we restrict the data analysis reported in this paper to contiguous blocks of 2^{23} time samples (17.5 min).

The data were de-dispersed to a reference dispersion measure (DM) of $24.6 \text{ cm}^{-3} \text{ pc}$, the DM of 47 Tuc C. This was done by delaying samples from the higher-frequency channels to account for the faster propagation through the ionized interstellar medium, before summing data from all channels into a one-dimensional time series. For the present analysis, where we are particularly interested in looking for binary pulsars with short orbital periods, this choice was made largely to keep the total computational effort manageable. The pulsars presently known in 47 Tuc exhibit a range of DMs between 24.1 and $24.7 \text{ cm}^{-3} \text{ pc}$ (Table 3). In the current analysis, any pulsar with a true DM that is within one unit of $24.6 \text{ cm}^{-3} \text{ pc}$ will have its pulse smeared by at most 1 ms as a result of this single-DM approximation.

As noted by a number of authors (Middleditch & Friedhorsky 1986; Johnston & Kulkarni 1991), standard pulsar search analyses, which look for significant harmonics in the power spectrum of a de-dispersed time series, suffer reductions in sensitivity to pulsars in short-period binary systems. The effect of

TABLE 2
LOG OF OBSERVATIONS AND DETECTIONS.

Date (MJD)	Number of integrations	C	D	E	F	G	H	I	J	L	M	N	O	Q	U
50683	16	0/4.6	2/7.0	14/19.8	0/2.3	0/2.5	10/17.0	0/2.4	6/8.8		0/2.5		0/2.9		
50686	16	4/7.6	0/3.2		0/4.4	16/33.5		0/3.4	16/12.2	0/3.1			4/10.1		
50689	16	5/9.8			0/3.1	0/3.4		0/2.9	11/12.9	0/2.8		16/18.2	0/2.7		
50690	16	16/21.9	0/2.8	0/3.2	0/6.1	0/3.3			1/6.6				3/8.6	0/2.0	
50739	5	5/20.9	3/10.2					0/7.4	5/31.5						
50740	8	0/4.4	1/7.2	0/7.2		0/3.7		2/8.8	8/13.4		0/3.8		0/5.3	7/13.5	0/4.2
50741	8		8/11.9	8/19.7				2/9.8	8/46.5				0/4.1	0/4.5	0/3.0
50742	8	8/15.7	0/4.1		2/6.5	0/3.1	8/16.6	0/6.1	6/12.6	0/4.0					0/4.0
50743	3	0/7.9			3/21.9	3/12.8			3/17.8						
50744	8	8/15.3		0/3.2	0/3.6	8/14.7		0/4.2	4/11.1				0/3.2		
50745	8	0/2.8	8/22.6		0/5.4		5/11.3	0/3.7	8/26.7				0/3.5		
50746	8	0/5.4	8/17.7		0/3.1		0/6.5	0/3.6	8/32.2					0/6.0	
50748	4	4/10.5	0/3.7			0/3.9					4/14.5		0/4.3		
50980	8	8/22.5	8/33.4	8/20.7	1/4.9				0/3.8			0/3.4		0/2.7	1/8.4
50981	16	16/63.2	5/9.3		15/18.8	1/4.2			7/7.9		1/6.3		0/3.0		
50982	16	2/5.8	16/22.7	9/13.3	1/5.7		0/2.5		3/5.4		1/8.5		0/4.3		
50983	4	0/5.0		3/12.6	0/6.3								0/7.4		0/5.6
50992	8	0/5.4	0/6.7		6/12.9				0/4.7						0/3.3
50993	8	8/40.2	0/7.2	0/5.4	0/2.9			1/9.1	8/22.8	7/11.8					0/3.0
50998	16	0/2.1	3/6.6	1/5.4	2/5.4				0/2.7			14/11.8			
50999	5	0/6.4	5/14.6		4/10.8			0/4.1	0/6.8				0/4.8		0/3.7
51000	16	0/6.7	0/2.1					0/2.7	2/6.7	0/3.1		0/2.3	0/2.6		0/2.2
51001	10	5/10.2	0/3.2				0/6.0		0/3.1					1/2.9	4/10.9
51002	16		2/5.5	1/7.4				0/2.8	16/146.3		0/2.2		3/6.4		3/7.7
51003	16		4/8.6	4/8.8	0/6.1	0/2.8	0/3.2	0/2.6	16/36.1				0/4.9		0/5.3
51004	16	0/5.8		0/5.7	12/12.6				13/16.2					10/10.2	0/3.0
51005	12	2/7.7	0/3.0		0/2.5				9/12.8	0/2.7					
51007	10	0/4.3	0/5.2						10/23.5				2/4.4	0/2.9	
51012	8	5/11.4		0/7.1	4/10.9	1/6.2			8/186.1				3/7.2		0/4.7
51026	16	16/25.1	0/4.4	0/4.0	0/3.0	0/3.6			4/8.3		0/2.2		0/3.2		0/2.4
51027	7	6/15.7	7/36.0	3/9.9				0/7.2	7/14.3		0/3.4				0/3.1
51029	5	0/4.4		1/9.5	0/5.4			0/4.1	5/26.2						
51031	6	0/3.1		0/4.7	4/10.2			0/6.7	3/8.0				0/5.1		0/7.1
51033	6		3/12.8			0/5.5			0/3.4					6/20.7	
51036	7	0/3.5	7/15.2		4/9.9				0/4.5				0/5.8	2/9.6	0/3.9
51037	16		16/34.1				0/2.6	0/4.6	16/29.7		0/3.8				0/2.2
51038	6	6/18.3	5/10.2		1/8.1			0/3.8					0/6.2	10/10.7	
51039	3	3/17.2	3/19.9	1/8.6			0/8.4	1/10.3							
51040	4	4/18.0	4/16.8			2/12.1		0/8.3	4/42.0						0/8.2
51085	16	5/8.9	10/9.6	0/2.8	0/3.0			0/2.1	16/16.5		0/3.2	0/3.2	0/5.0		0/3.4
51086	16	16/27.9	0/2.9			0/2.2	15/17.4		16/44.5	0/5.0			1/6.2		0/2.3
51088	19	0/2.2	0/2.9		0/2.8	0/1.9	1/5.7	0/1.9	8/13.0		0/2.2		0/2.7		
51089	4	4/13.6		0/4.8				3/10.3	0/5.1		0/4.6				
51090	4	4/23.2	4/20.5		0/5.7				4/16.7						0/7.9
51091	4	4/49.3	4/21.3				4/21.2	1/9.3							
51092	8	8/29.4	7/15.5	1/7.7	8/29.3			5/13.4	0/4.8		0/6.4			0/2.8	0/4.5
51093	8	0/6.8	0/3.5		0/3.2			0/4.6					3/6.7		
51095	4	4/18.0		0/6.8				3/11.8	1/10.7						
51096	5	4/30.5	5/16.4		0/4.5				0/4.8						
51097	12	3/9.8	4/12.2		7/18.2		1/5.2		12/88.3		8/11.2		0/3.7		
51098	16	15/17.8	0/2.4	0/3.7					0/2.9	2/6.6					
51099	19	0/2.7	4/6.9	18/28.6	1/3.8				0/3.6				0/2.6		10/8.2
51100	16	0/3.5	0/2.4			0/3.5	1/6.0		16/16.5						0/6.3
51101	17	16/23.5	0/2.3						10/8.7						0/2.8
51145	16	0/3.0	10/14.8	16/12.6	7/9.0				16/18.1			0/2.3			
51146	16	3/6.8	0/4.9		0/3.4				2/6.6						
51147	8	0/3.5		0/5.5											6/11.6
51148	5	1/3.6	5/31.2						0/13.4						0/6.4
51149	16	0/5.4	0/5.1			0/2.4		0/2.6	13/11.4	0/2.9	0/2.1		0/2.3	0/2.5	1/5.2
51150	16	0/5.4		0/2.8				0/2.2	14/22.7	0/2.3			0/4.0		
51151	9	2/7.7	9/15.1						2/5.3						
51152	17	1/6.2	4/7.6		0/2.8			0/2.5	16/14.5				0/4.6		3/7.3
51153	16	0/3.0	0/4.0	0/2.7		0/5.4	1/4.8		15/16.1			0/2.0			
51154	19	19/69.6	5/9.0					0/2.3	12/14.5				0/2.7		
51155	16	14/18.1	0/2.1	0/4.8			0/2.5	0/2.9	11/9.9			0/6.2	1/6.0	0/2.2	
51156	16	10/49.0	3/6.1	4/14.4	16/32.0				16/52.2						
51157	6	0/6.9	6/23.2					0/3.2	6/53.2						
51211	16	0/5.5	2/6.4	15/20.3	4/6.4	0/2.0	0/4.6	0/3.2	0/2.2	0/2.2			1/4.1		0/2.7
51212	16	3/5.6	0/3.8		0/2.1	0/2.9		0/2.1	16/38.6			0/2.7	0/2.3	0/2.8	
51213	16		4/6.0	0/2.6	0/2.1	0/7.1		0/2.8	0/2.8				15/13.7		13/14.1
51214	16	2/5.9	0/2.5		0/2.9		0/2.1	0/3.7	16/18.5				0/3.3		
51215	16	3/6.2	0/2.1	0/2.5	15/13.2	0/2.1	0/3.0	0/2.1	2/5.4				11/12.4		
51216	16	9/9.7	1/6.1	10/10.0	9/9.4			0/2.8	9/10.4				15/19.7		
51217	16	0/4.0	0/4.3	0/3.6		0/2.7	7/8.4	0/2.8	14/28.8				0/3.1		0/2.9
51218	16	2/8.6	0/2.6	0/3.9	0/5.0			0/2.8	16/24.1				0/4.7		4/7.0

NOTE.—For each observing date we list the number of 17.5 min integrations that were independently searched. For each pulsar on each day we list the number of integrations in which the pulsar was detected with the search code according to the criteria summarized in §4; and the signal-to-noise ratio (σ) scaled to a 17.5 min integration, obtained from summing the entire day's data set using the best pulsar ephemeris available (e.g., on MJD 51004, 47 Tuc C was not detected in any of 16 integrations with $\sigma \geq 9$, but all data added together using the pulsar's ephemeris yielded $\sigma = 23.2$, or an average of $\sigma = 5.8$ per integration. Hence the 0/5.8 notation. For 47 Tuc D, even adding all data did not yield an unambiguous detection — one with $\sigma \gtrsim 7$ — and so the respective entry is blank).

TABLE 3
PULSE PERIODS, DISPERSION MEASURES, DUTY-CYCLES, AND FLUX DENSITIES AT 20 CM.

Pulsar	Period (ms)	DM (cm ⁻³ pc)	w ₅₀ (%)	Flux density (mJy)
Previously Known				
47 Tuc C	5.756780	24.6	13	0.36(4)
47 Tuc D	5.357573	24.7	10	0.22(3)
47 Tuc E	3.536329*	24.3	25	0.21(3)
47 Tuc F	2.623579	24.4	14	0.15(2)
47 Tuc G	4.040379	24.4	13	0.05(2)
47 Tuc H	3.210341*	24.4	13	0.09(2)
47 Tuc I	3.484992*	24.5	14	0.09(1)
47 Tuc J	2.100634*	24.6	15	0.54(6)
47 Tuc L	4.346168	24.4	15	0.04(1)
47 Tuc M	3.676643	24.4	25	0.07(2)
47 Tuc N	3.053954	24.6	11	0.03(1)
Newly Discovered				
47 Tuc O	2.643343*	24.4	12	0.10(1)
47 Tuc P	3.643021*	24.3	15	...
47 Tuc Q	4.033181*	24.3	11	0.05(2)
47 Tuc R	3.480463*	24.4	15	...
47 Tuc S	2.830*	24.4	9	...
47 Tuc T	7.589*	24.6	17	...
47 Tuc U	4.342827*	24.3	8	0.06(1)
47 Tuc V	4.810*	24.1	7	...
47 Tuc W	2.352344*	24.3	17	...

NOTE.—Uncertainties in barycentric period and DM are one or less in the last digits quoted.

*Binary pulsar (see Table 5).

the binary motion is to cause a change in the apparent pulse frequency during the integration, spreading the emitted signal power over a number of spectral bins, thereby reducing the apparent signal-to-noise ratio. In order to recover the signal, it is necessary to transform the time series to the rest frame of an inertial observer with respect to the pulsar before carrying out the periodicity search. This transformation is readily achieved by applying the Doppler formula to relate a time interval in the pulsar frame, τ , to the corresponding interval in the observed frame, t :

$$\tau(t) = \tau_0(1 + v(t)/c), \quad (1)$$

where $v(t)$ is the observed radial velocity of the pulsar along the line-of-sight, c is the speed of light, and we have neglected terms in (v/c) of order higher than the first. Ideally, if the orbital parameters of the binary system are known, $v(t)$ can be calculated from Kepler’s laws. For the purposes of a blind search, where the orbital parameters are a priori unknown, assuming a Keplerian model for $v(t)$ would require a five-dimensional search of all the parameter space — a computationally non-trivial task! The search can, however, be considerably simplified by assuming that the orbital acceleration a is constant during the observation, i.e., $v(t) = at$. This assumption is commonly used in searches of this kind (Anderson 1992) and turns out to be reasonable over a wide range of orbital parameters, phases, and observation lengths. We investigate this in more detail in §5.1.1.

Given a prescription for $v(t)$, the re-sampling process is straightforward. The time intervals in the new frame are calculated from equation 1. New sample values are then created based on a linear interpolation running over the original time series (see also Middleditch & Kristian 1984). We choose to define the value of τ_0 such that τ is equal to the original sam-

pling interval, t_{samp} , at the mid-point of the integration. For the condition $v(t) = at$, it follows that

$$\tau_0 = \frac{t_{\text{samp}}}{1 + aT/2c}, \quad (2)$$

where T is the integration time, 17.5 min in our case. This condition guarantees that, under the approximations made here, the number of samples in the corrected time series is the same as in the original one. The re-sampling process is relatively trivial in terms of computation time and can be readily carried out for a number of trial accelerations for each de-dispersed time series in order to effect a search in “acceleration space”.

In all the analyses carried out in this paper, each de-dispersed time series was re-sampled and analyzed for a number of trial accelerations in the range $|a| < 30 \text{ m s}^{-2}$. Most pulsars in presently known binary systems typically undergo accelerations of up to about 5 m s^{-2} . There are however other binary systems where more extreme accelerations have motivated us to search a larger range of acceleration space. These include the double neutron-star binary PSR B2127+11C in M15, originally discovered at a trial acceleration of -9.5 m s^{-2} (Anderson et al. 1990), and the eclipsing binary PSR B1744–24A in Terzan 5 (Lyne et al. 1990), where the maximum line-of-sight acceleration is 33 m s^{-2} .

The step size between each trial acceleration was 0.3 m s^{-2} . Some care is required when choosing this interval in order to strike a compromise between unnecessary processing time incurred by oversampling the parameter space and the loss of sensitivity caused by undersampling. Assuming that the constant acceleration approximation adequately describes the Doppler shifts during the integration, it follows that the number of spectral bins across which a signal will drift due to the assumed trial

acceleration being different from the true value by an amount Δa is given by $\Delta a \times T^2/Pc$, where P is the pulse period. Our choice of step size thus guarantees that any pulsar period or harmonic with a period greater than 2 ms will not drift by more than one spectral bin during the 17.5 min integration.

Following the de-dispersing and re-sampling procedures outlined above, each time series is analyzed independently according to standard pulsar search techniques. The analysis procedure is very similar to that described in detail by Manchester et al. (1996). In brief, we compute discrete Fourier transforms of each time series, and sum harmonically related spectral components for 1, 2, 4, 8, and 16 harmonics in turn, in order to maintain sensitivity to a variety of pulse profile relative widths, or duty-cycles. For each harmonic sum, candidates are ranked in order of spectral signal-to-noise ratios³. At this stage, all spectral features with $\sigma \geq 6$ are stored, along with the period of the signal.

Once computations are completed for the time series corresponding to all trial accelerations for a 17.5 min block of data, we plot σ versus trial acceleration for multiple occurrences of each period, within a suitable tolerance, detected above a pre-defined “significance” threshold. This threshold can be estimated theoretically from the statistics of the phase-space searched, but practical considerations (such as the presence of radio-frequency interference) result in our determining this value empirically. We generate plots such as that in Figure 1 for all cases where at least one detection of a multiply detected period has $\sigma \geq 9$.

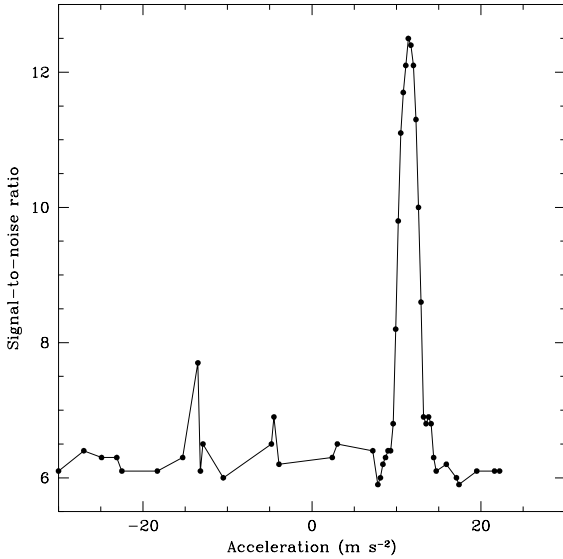


FIG. 1.— Signal-to-noise ratio (σ) versus trial acceleration for the discovery of 47 Tuc R. This plot corresponds to one of seven 17.5 min integrations, out of a total of eight on MJD 50742, in which σ in at least one trial acceleration was higher than the threshold of 9. Most points with $\sigma \lesssim 8$ correspond to random noise rather than detection of the pulsar.

3. SENSITIVITY

To estimate the sensitivity of our search we calculate the minimum flux density S_{\min} that a pulsar must have in order to be

detectable. Following Dewey et al. (1984), this is given by

$$S_{\min} = \frac{\sigma \eta S_{\text{sys}}}{\sqrt{n \Delta \nu T}} \left(\frac{w}{P-w} \right)^{1/2}. \quad (3)$$

Here σ is the signal-to-noise ratio threshold of the survey (9 in our case); η is a constant that takes account of losses in sensitivity due to digitization of the incoming data and other inefficiencies in the system (~ 1.5 for our system); S_{sys} is the system equivalent flux density (~ 35 Jy for the present system in the direction of 47 Tuc); n is the number of polarizations summed (two in our case); $\Delta \nu$ is the total observing bandwidth (288 MHz); T is the integration time (1049 s); and w and P are the pulse width and period respectively.

The observed pulse width w in the above expression is in general greater than the intrinsic width w_{int} emitted at the pulsar because of the dispersion and scattering of pulses by free electrons in the interstellar medium, and the post-detection integration performed in hardware. Interstellar scattering is negligible for most observations toward 47 Tuc, which is relatively nearby and located well away from the Galactic plane. The observed pulse width for unaccelerated pulsars will therefore be the convolution of the intrinsic pulse width and broadening functions due to dispersion and integration, and can be estimated from the quadrature sum

$$w^2 = w_{\text{int}}^2 + t_{\text{DM}}^2 + t_{\Delta \text{DM}}^2 + t_{\text{samp}}^2. \quad (4)$$

Here t_{DM} is the dispersion broadening across one filter bank channel, $t_{\Delta \text{DM}}$ is the overall pulse broadening due to the difference between the single DM at which we de-disperse all data and the true DM of a pulsar (ΔDM), and t_{samp} is the data sampling interval (125 μs in our case). The dispersion broadening across a single channel is calculated using the standard expression

$$t_{\text{DM}} = 8.3 \left(\frac{\text{DM}}{\text{cm}^{-3} \text{ pc}} \right) \times \left(\frac{\Delta \nu_{\text{chan}}}{\text{MHz}} \right) \times \left(\frac{\nu}{\text{GHz}} \right)^{-3} \mu\text{s}, \quad (5)$$

which is valid for $\Delta \nu_{\text{chan}} \ll \nu$ as in our case where $\Delta \nu_{\text{chan}} = 3$ MHz and $\nu = 1374$ MHz. The effective time resolution for these 47 Tuc observations, calculated from equation 5 and the sample time, at a DM of $25 \text{ cm}^{-3} \text{ pc}$, is approximately 0.3 ms at the center frequency of observations, although it falls to 0.4 ms at the low-frequency end. However in many cases the effective time resolution is limited by the $t_{\Delta \text{DM}}$ term in equation 4, which amounts to $0.9 \left(\frac{\Delta \text{DM}}{\text{cm}^{-3} \text{ pc}} \right) \text{ ms}$ at 1374 MHz.

Figure 2 shows the search sensitivity as a function of period for a 17.5 min integration based on equations 3–5. Here we have assumed a box-car pulse shape and an intrinsic duty-cycle of 15%, typical of many among the pulsars known in 47 Tuc. It can be seen that the present system is sensitive to most pulsars in 47 Tuc with $P > 2$ ms and with average 20 cm flux densities above 0.3 mJy during a 17.5 min integration.

³Spectral signal-to-noise ratios are defined throughout this paper to be the height of a feature in the amplitude spectrum divided by the spectral rms. In general, spectral signal-to-noise ratios and ratios calculated from reconstructed time-domain pulse profiles are different, although in practice, for relatively low values — relevant for search sensitivity calculations (§3; §5.1.1) — they are identical, and we use the nomenclature σ in both instances. To estimate average flux densities (§5.6), where some signal-to-noise ratios are large, we carry out all computations in the time domain.

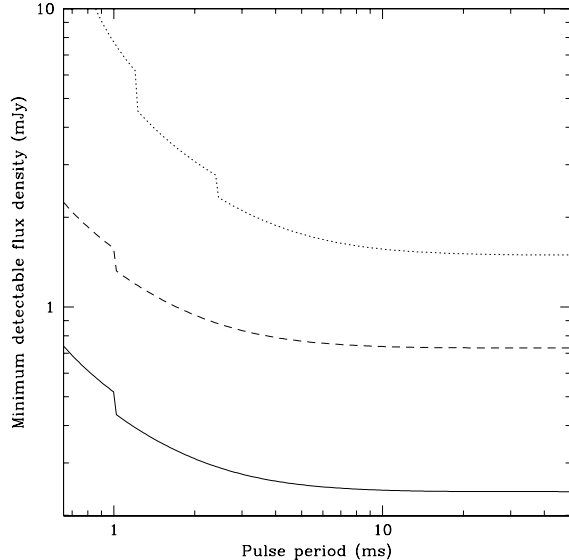


FIG. 2.— Sensitivity as a function of pulse period. The solid curve is the sensitivity calculated for our 20 cm observations, for an assumed pulsar duty-cycle of 15%, analyzed in individual 17.5 min blocks. The steps in the curves going from right to left reflect loss of power in the frequency domain as higher-order harmonics drop out of the spectrum. The dotted curve is an estimate of the sensitivity at 50 cm for the observations reported by Manchester et al. (1990, 1991), for an integration time of 42 min. The dashed curve scales the 20 cm curve to a wavelength of 50 cm assuming a pulsar spectral index of -1.6 .

The improvement in sensitivity provided by the new 20 cm system is apparent when comparing its sensitivity curve to that based on a 42 min observation assuming the parameters of the 50 cm system used by Manchester et al. (1990, 1991) to discover pulsars 47 Tuc C–M, also shown in Figure 2. For flat spectrum sources one may compare the 20 and 50 cm curves directly. A more realistic comparison between the two searches is shown by the scaled version of the present 20 cm curve assuming the typical pulsar spectral index of -1.6 . With this assumption we see that the present system represents as much as a threefold improvement in sensitivity for a ~ 2 ms pulsar such as 47 Tuc J.

The sensitivity calculations described in this section take no account of the effects of the degradation in σ of any binary pulsar whose apparent period may change significantly during the 17.5 min integration. We investigate this issue in detail in §5.1.1.

4. RESULTS

We have reduced all data listed in Table 2 in the manner described in §2. In this table we list the number of 17.5 min integrations analyzed on each day, giving both the number of daily integrations in which the search code detected the pulsar — i.e., in which $\sigma_{\text{search}} \geq 9$ — and the average daily σ , scaled to a 17.5 min integration, obtained from summing all data for that day using the pulsar’s ephemeris. We detected some 50 distinct periods for which the σ vs. trial acceleration plots are broadly similar to that of Figure 1, i.e., have a clearly defined and significant maximum in trial acceleration. Eleven of these we identified with previously known pulsars in 47 Tuc.

4.1. Previously Known Pulsars

The detection rate for the previously known pulsars ranges from 10% (47 Tuc N), to 90% (47 Tuc C and J), with all but

two of the 11 pulsars detected on at least 25% of the observing days. In contrast, at 50 cm, all but 47 Tuc C are detected less than 25% of the time, and the same is true at 70 cm for seven of the pulsars (Robinson 1994). The detection rates with the new observing system are clearly much higher than with past observations, leading to improved parameters for most pulsars.

In Table 4 we present “phase-connected” timing solutions for three previously known pulsars, obtained from 20 cm data collected since 1997 October. To determine these we first make time-of-arrival (TOA) estimates by cross-correlating pulse profiles, obtained by summing several minutes’ worth of data for a pulsar on a given day, with a high- σ “standard profile”, and adding the time delay to the start-time of the integration, appropriately translated to the mid-point of the integration. We then use the TOAs, and a model describing the pulsars, including astrometric, spin, and (where relevant) binary parameters, to obtain improved parameters. These are derived by minimizing the timing residuals (difference between observed and computed pulse phases) in a least-squares sense. This procedure is implemented in the TEMPO software package (<http://pulsar.princeton.edu/tempo>).

The timing solutions for 47 Tuc C and D match those first presented by Robinson et al. (1995), obtained from 50 and 70 cm data. The phase-coherent solution for 47 Tuc J is a new one. The small limit on its orbital eccentricity is perhaps somewhat surprising, since it suggests a lack of strong recent interactions with other stars, while its position well outside the cluster core tends to suggest the opposite. However it is also conceivable that tidal dissipation in a Roche lobe-filling companion could circularize the orbit quickly (cf. §5.4). We remark in passing that a 20 cm continuum map of the central regions of 47 Tuc shows three relatively bright, variable, point sources (Fruchter & Goss 1999). Two of these are clearly associated with 47 Tuc C and D. The third, whose position differs from that listed for 47 Tuc J in Table 4 by 0:07(3) in right ascension and 0:3(2) in declination, and whose average flux density of 0.6 mJy matches our average of 0.5 mJy (§5.6), can now be identified with 47 Tuc J.

There is no evidence that 47 Tuc L is a binary pulsar (a possibility according to Robinson et al. 1995). We have detected this pulsar on 11 separate occasions spanning over 500 days (Table 2), and the barycentric period is constant (see Table 3, which lists the pulse periods, DMs, and observed duty-cycles of all pulsars detected in our observations).

Finally, we were also able to determine the eccentricity for 47 Tuc E, and obtain a binary solution for 47 Tuc H. The very significant eccentricities for these systems (Table 5) are unique among this class of binaries: in the disk of the Galaxy such systems have $e \lesssim 10^{-5}$ (Camilo 1999). The eccentricities are presumably fossil evidence of interactions near the dense cluster core, and may be due to perturbations by passing stars, or stellar exchange interactions (see Rasio & Heggie 1995 and Heggie & Rasio 1996 for details). It will be interesting to see if other wide systems in this cluster have large eccentricities.

4.2. Newly Discovered Pulsars

Nine of the remaining periods detected in our data appeared in at least two 17.5 min integrations on one day, with some being detected in most integrations. For each detection of such a period, we de-dispersed the raw data at several trial values of DM about the nominal DM. In all nine cases there was a clearly defined maximum signal-to-noise ratio as a function of DM, ensuring that the periodic signals were truly dispersed. Af-

TABLE 4
TIMING SOLUTIONS OF THREE PULSARS.

Parameter	J0023–7204C	J0024–7204D	J0023–7203J
Right ascension, α (J2000)	00 ^h 23 ^m 50 ^s .350(1)	00 ^h 24 ^m 13 ^s .877(2)	00 ^h 23 ^m 59 ^s .4057(6)
Declination, δ (J2000)	−72°04′31″.486(3)	−72°04′43″.845(9)	−72°03′58″.781(2)
Period, P (ms)	5.7567800118(2)	5.3575732858(1)	2.100633545861(1)
Period derivative, \dot{P}	$-5.1(1) \times 10^{-20}$	$-0.31(4) \times 10^{-20}$	$-0.96(1) \times 10^{-20}$
Epoch of period (MJD)	47858.5	48040.7	51000.0
Dispersion measure, DM (cm ^{−3} pc) ...	24.6	24.7	24.6
Orbital period, P_b (d) .....	...	...	0.120664939(1)
Projected semi-major axis, x (s) .....	...	...	0.040411(1)
Eccentricity, e .....	...	...	< 0.0001
Longitude of periastron, ω .....	...	...	0.0
Time of periastron, T_0 (MJD) .....	...	...	51000.765678(1)
Post-fit rms timing residual (μ s)	10	19	9
$\alpha - \alpha_{47 \text{ Tuc}}$	−15 ^s .6	8 ^s .0	−6 ^s .5
$\delta - \delta_{47 \text{ Tuc}}$	19′′.6	7′′.3	52′′.3
Pulsar–cluster center offset (core radii)	6	3	5

NOTE.—Figures in parentheses represent uncertainties in the last digits quoted, given for all fitted parameters.

ter viewing the corresponding time-domain pulse profiles, and judging them suitably “pulsar-like”, we felt secure in identifying each of these nine periods with previously unknown pulsars in 47 Tuc. Table 6 lists detections for the newly discovered pulsars that are seen only occasionally.

For all nine of the newly detected pulsars, the period changed within an observing day in a manner consistent with the Doppler shifts arising in binary systems. Only three of the nine pulsars (47 Tuc O, Q and U) were detected on many occasions (Table 2). Fortunately, three of the remaining six (47 Tuc P, R, and W) have such short orbital periods that it was possible to cover more than an entire orbit on their discovery days, and hence establish good orbital parameters (see Fig. 3). Binary parameters for all pulsars are summarized in Table 5.

Most of the newly discovered pulsars appear to be similar in their binary characteristics to the previously known pulsars in the cluster. For instance, 47 Tuc O, P, and R have short orbital periods ($P_b \sim 1.5\text{--}5.5$ h) and low companion masses ($m_2 \sim 0.03 M_\odot$), similar to the previously known 47 Tuc I and J. Although the period of 47 Tuc R, at 96 min, is considerably shorter than that of 47 Tuc J, there is no reason to suspect that these systems are fundamentally different.

In contrast, 47 Tuc Q and U are similar to 47 Tuc E and H, with $m_2 \sim 0.2 M_\odot$; the companion stars are presumably low-mass helium white dwarfs much like those found in similar systems in the Galactic disk (e.g., Lundgren, Foster, & Camilo 1996). The binary periods for 47 Tuc Q and U are somewhat shorter than the corresponding ones for 47 Tuc E and H (0.4–1.2 d vs. 2.3 d; see Table 5), but we believe this betrays no fundamental difference between the various systems. We have not yet obtained orbital parameters for 47 Tuc S and T, but from the observed projected velocity change during the discovery days (−5 and 12 km s^{−1} over 2 h, respectively; see Fig. 3) we believe they also fall into this higher-mass group.

It thus appears the vast majority of the binary pulsars known to date in 47 Tuc fall into one of two classes. However, the two pulsars discovered most recently, 47 Tuc V and W, are not so easily categorized.

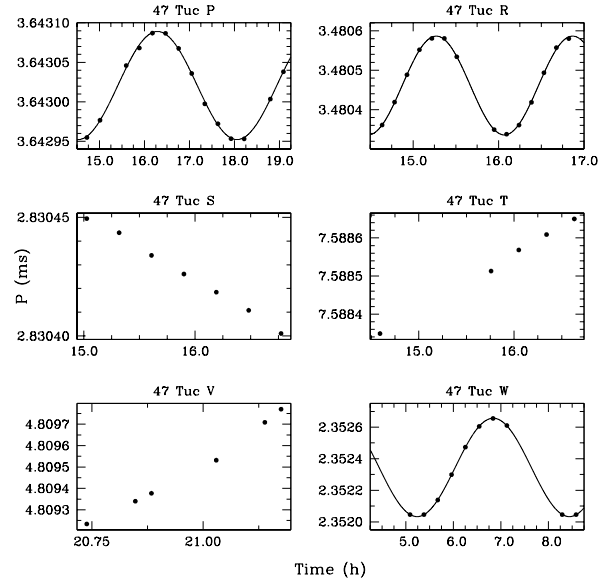


FIG. 3.— Observed barycentric periods for six newly discovered pulsars that are seldom detected. Each period is based on 17.5 min of data, with the exception of 47 Tuc R (8.7 min) and 47 Tuc V (2.2 min), and corresponds to $\sigma \geq 6$. Times are given in UT on discovery day (see Table 6).

Pulsar 47 Tuc V has been detected on two different days, at seemingly identical orbital phases (with period increasing as a function of time, hence on the “near-side” of its companion — see Fig. 3), and it displays an apparent orbital velocity change of up to ~ 80 km s^{−1} in under one hour. The observed change in period during this time leads us to believe that the orbital period is several hours, suggesting a relatively massive companion. Another unusual aspect of this system is that it was detected on both occasions with relatively large signal-to-noise ratios in several 2 min sub-integrations, but interspersed with non-detections (Fig. 3), as if it were being irregularly eclipsed, despite its orbital phase⁴.

⁴In practice it is usually easy to distinguish among interstellar scintillation and eclipses by a companion as the cause for the temporary non-detection of a pulsar. Eclipses tend to occur with the pulsar roughly centered at superior conjunction, while scintillation has no preferred orbital phase. Also, scintillation has characteristic

TABLE 5
BINARY PARAMETERS.

Pulsar	P_b (d)	x (s)	T_0 (MJD)	ω (deg)	e	m_2^* (M_\odot)
Previously Known						
47 Tuc E	2.2568448	1.98184	51004.05	219	0.0003	0.19
47 Tuc H	2.3576966	2.15281	51000.9735	110	0.071	0.20
47 Tuc I	0.2297923	0.03846	50740.5794	0.0	0.0	0.02
47 Tuc J	0.1206649	0.04041	51000.7657	0.0	0.0	0.03
Newly Discovered						
47 Tuc O	0.1359743	0.04515	51000.0212	0.0	0.0	0.03
47 Tuc P	0.1472	0.0380	50689.6789	0.0	0.0	0.02
47 Tuc Q	1.1890840	1.46219	51002.175	0.0	0.0	0.21
47 Tuc R	0.0662	0.0334	50742.6365	0.0	0.0	0.03
47 Tuc S	†	...	...	...	...	...
47 Tuc T	†	...	...	...	...	...
47 Tuc U	0.4291057	0.52696	51002.645	0.0	0.0	0.15
47 Tuc V	$\sim 0.2?$	...	...	...	...	...
47 Tuc W	0.1330	0.2435	51214.950	0.0	0.0	0.15

NOTE.—Uncertainties in all fitted parameters are one or less in the last digits quoted.

* Assumes a pulsar mass of $1.4 M_\odot$ and inclination angle for the orbit of $i = 60^\circ$.

† About one to several days.

Pulsar 47 Tuc W, with an orbital period of 3.2 h, may resemble short-period binary systems such as 47 Tuc J, and the pulsed radio signals are apparently eclipsed for a fraction of its orbit, as in some of these systems (see §5.4). However its implied companion mass, at $\sim 0.15 M_\odot$, is a factor of ~ 6 higher than that of those systems, more typical of a low-mass white-dwarf. But if the companion were indeed a white dwarf, we would not expect eclipses. We consider it possible that this system is somewhat akin to PSR B1744–24A, located in the cluster Terzan 5, with $P_b \sim 1.8$ h, $m_2 \sim 0.10 M_\odot$, and displaying irregular eclipses (Lyne et al. 1990; Nice & Thorsett 1992).

There remain about 30 periodic signals that displayed several pulsar-like characteristics, but that were detected on only one integration of one day. We regard several of these as good pulsar candidates, potentially to be confirmed by future observations.

5. DISCUSSION

5.1. Survey Limitations

Although the recent observations of 47 Tuc have been successful beyond our most optimistic expectations, it is important to keep in mind the many and severe selection effects inherent in the data and analyses reported on in this paper. The greatest of these, particularly for short-period binary systems, has to do with the extent of parameter space that has been covered by our “acceleration searches”.

5.1.1. Sensitivity to Binary Pulsars

In addition to the improvements in sensitivity over previous searches of 47 Tuc enabled by the new 20 cm observing system, use of an acceleration search has significantly improved the

time-scales and amplitudes. No other pulsar in 47 Tuc displays the deep intensity modulations on time-scales of about a minute observed for 47 Tuc V, and we therefore suggest the eclipse interpretation.

⁵In effect this suggests that without the acceleration code we would have discovered five new pulsars, an increase of $\sim 50\%$ over the previously known population. This is surprising, considering the factor of ~ 3 improvement in sensitivity claimed in §3. This estimate relied on assuming a spectral index of -1.6 for pulsars in 47 Tuc. Perhaps this assumption is not valid, and the average spectral index for millisecond pulsars in 47 Tuc is smaller than -1.6 .

ability to find binary pulsars. Prior to this survey only four out of 11 (36%) millisecond pulsars known in 47 Tuc were members of binary systems. The new discoveries bring the number of binary pulsars in 47 Tuc to 13 (65% of the total). We consider it highly significant that all of the new millisecond pulsars reported here are members of binary systems. These discoveries are in spite of the fact that, as demonstrated in §3, the sensitivity to isolated pulsars is significantly improved over the previous surveys by Manchester et al. (1990, 1991) and Robinson et al. (1995). We note that three of the five brightest pulsars in 47 Tuc at 20 cm are isolated (Table 3); if significant, this may suggest that isolated pulsars in 47 Tuc have a relatively high intrinsic luminosity cutoff. Also, isolated pulsars in 47 Tuc might have, on average, a larger spectral index than binary pulsars. Finally, the specific incidence of isolated pulsars in 47 Tuc might be low. A combination of these factors could explain why our more sensitive survey has failed to find additional isolated pulsars.

The improved sensitivity of the acceleration search to short-period binaries is demonstrated by the fact that four of the nine binary systems we found, 47 Tuc P, R, S and V, would not have been discovered without the use of the acceleration code since, in each case, the signal-to-noise ratio never rose above the threshold of 9 at a trial acceleration of zero⁵. Despite searching an acceleration range of $|a| < 30 \text{ m s}^{-2}$, most of the new discoveries and detections of previously known pulsars occurred at $|a| < 5 \text{ m s}^{-2}$. Three notable exceptions are 47 Tuc R, V, and W, that displayed maximum line-of-sight accelerations of 11.4, 23.7, and 21.3 m s^{-2} respectively (e.g., Fig. 1).

While it is clear that this survey has improved the knowledge of the true fraction of binary pulsars in 47 Tuc, an outstanding

TABLE 6
RARELY DETECTED PULSARS.

Pulsar	Date (MJD)	Number of integrations	Detections/ σ
47 Tuc P	50689	16	5/6.3
47 Tuc R	50742	8	7/8.9
47 Tuc S	50741	8	3/9.9
47 Tuc T	50746	8	4/9.3
	51005	8	0/5.4
	51040	4	4/25.8
47 Tuc V	51012	8	2/3.4
	51055	16	3/4.4
47 Tuc W	51214	16	9/10.0

question that remains is the extent of binary parameter space probed by the present search strategy. In this section we attempt to answer this by exploring the limits of the present search with respect to a variety of short orbital period binary systems. In what follows, when we use the term “acceleration search” we are explicitly referring to the one-dimensional (i.e., constant acceleration) approximation outlined in §2.

For the purposes of this discussion it is useful to note that most observed binary pulsar systems in 47 Tuc fall broadly into two categories: those with orbital periods of order 0.4–2.3 d and companion masses $\sim 0.2 M_{\odot}$ (47 Tuc E, H, Q, U, and probably S and T) and 47 Tuc I, J, O, P, and R, which are characterized by shorter orbital periods (1.5–5.5 h) and lighter companions ($m_2 \sim 0.03 M_{\odot}$). (The nature of 47 Tuc V and W is unclear at present.) We shall refer to these types here respectively as the “normal” and “short-period” binary systems, investigating the sensitivity of our search to both types in turn. In addition, since all the presently known binary systems have essentially circular orbits, we also investigate the search sensitivity to putative binary systems in which the pulsar is in an eccentric orbit about a more massive companion.

The first, and really only, detailed study of the degradation in sensitivity of a radio pulsar search for short orbital period systems was carried out by Johnston & Kulkarni (1991; hereafter JK). By calculating the decrease in amplitude of the signal in the Fourier power spectrum for a binary pulsar relative to a solitary one, and mathematically describing the signal recovery technique involved in the acceleration search, JK were able to quantify the degradation in sensitivity of pulsar search codes with and without acceleration schemes of the type used here. As their main example, JK considered a 1000 s observation of a $1.4 M_{\odot}$ pulsar in a circular orbit with a $0.3 M_{\odot}$ companion for a wide variety of orbital and pulse periods. Given that our 17.5 min analyses correspond to a similar integration time, JK’s results are highly relevant to this discussion. In addition, the $0.3 M_{\odot}$ companion considered by JK closely resembles the class of normal binary systems defined above.

We focus on Figure 4 of JK, which shows the net gain in sensitivity of an acceleration search when making multiple observations of the same system. In their example, JK assumed five independent observations of the binary at random orbital phases. From this figure we see that, for a 10 ms pulsar, the acceleration search allows one to detect binary systems with orbital periods of order four times shorter than a standard pulsar search code. The gain increases still further for shorter period pulsars, where the blurring of harmonics in the power spectrum

becomes even more pronounced. For a 3.5 ms pulsar, similar to 47 Tuc E and H, we infer from Figure 4 of JK that the acceleration analysis allows the detection of a binary with an orbital period about six times shorter than the standard search.

The results of JK are not directly applicable to the population of short-period binaries in 47 Tuc. Presently, the 3.48 ms pulsar 47 Tuc R, with an orbital period of 96 min, is the shortest orbital period system of this type. In order to estimate the sensitivity of our search code to even shorter period binaries with low-mass companions like 47 Tuc R, we generated a number of time series containing a synthetic 3.48 ms pulsar whose period was modulated as in a circular Keplerian orbit with a low-mass companion. We considered four separate cases corresponding to orbital periods of 90, 60, 30 and 15 min. The first value considered is similar to that of 47 Tuc R; the last value is close to that of the shortest orbital period known for any binary system: the 11 min orbit of the X-ray burst source X1820–303 in the globular cluster NGC 6624 (Stella, Priedhorsky, & White 1987).

In each case the mass function was held constant at $8.68 \times 10^{-6} M_{\odot}$ (similar to that of 47 Tuc R). To quantify the improvement gained by using the acceleration code, we generated a control time series containing a fake 3.48 ms pulsar with a fixed period but otherwise identical to the other simulations. In a similar sense to JK, we define the efficiency factor γ as the detected σ of the binary pulsar divided by that of the control pulsar. In order to compare the relative efficiency of the non-accelerated and accelerated analyses, separate values of γ were computed: γ_0 is the efficiency for the non-accelerated analysis, and γ_A is the equivalent parameter for the acceleration search in the analysis of the same data, performed as described in §2. By definition $0 \leq \gamma \leq 1$, with a value of unity signifying that no loss of signal occurred. In each case, the simulations were performed over all orbital phases to establish the response of the search code to the full range of orbital accelerations.

The results of the simulations are summarized in Table 7, where we list the range of efficiencies, as well as the mean values averaged over all orbital phases. As expected, the efficiencies for both the normal (γ_0) and acceleration search code (γ_A) are strong functions of orbital phase. In Table 7 we also list the “improvement factor” $I \equiv \gamma_A/\gamma_0$, the net gain in signal achieved by employing the acceleration search, averaged by time spent at each orbital phase. These simulations show a significant improvement in sensitivity gained when using an acceleration search. In particular for orbital periods as short as one hour (cases 1 and 2) the efficiency of the acceleration

TABLE 7
SEARCH CODE TESTS ON SIMULATED DATA.

Case	Period (ms)	P_b (min)	f (M_\odot)	e	$\gamma_{0,\min}$ (%)	$\overline{\gamma_0}$ (%)	$\gamma_{0,\max}$ (%)	$\gamma_{A,\min}$ (%)	$\overline{\gamma_A}$ (%)	$\gamma_{A,\max}$ (%)	I
1	3.48	90	8.68×10^{-6}	0.0	33	48	75	80	88	99	1.8
2	3.48	60	8.68×10^{-6}	0.0	26	39	58	68	75	86	1.9
3	3.48	30	8.68×10^{-6}	0.0	24	33	41	38	45	51	1.4
4	3.48	15	8.68×10^{-6}	0.0	18	23	28	30	32	35	1.4
5	34.8	60	0.13	0.7	0	48	78	18	63	92	1.3
6	34.8	30	0.13	0.7	0	33	63	20	43	69	1.3

NOTE.—For each case considered, the columns list the assumed pulse period, orbital period, mass function, and orbital eccentricity. The remaining columns show the range and average values of efficiencies of the search code for a normal analysis, γ_0 , and using an acceleration search, γ_A . The averaged “improvement factor” $I \equiv \gamma_A/\gamma_0$ is also given. Averaging over orbital phases has been appropriately weighted by the time spent at each phase.

search is at least 70% for any orbital phase, more than twice the efficiency of the normal search code.

For the shortest orbital periods of this type considered (cases 3 and 4), the acceleration search continues to be more efficient than the normal search although the improvement factor is smaller. In these cases the integration is becoming an increasingly significant fraction of the orbital period. As a result, the constant acceleration approximation used in the search (§2) ceases to hold. Among possible improvements to this strategy, the most straightforward approach is to perform one-dimensional acceleration searches on shorter segments of data. One can also include the acceleration derivative term in the prescription for $v(t)$. Although this necessarily adds a dimension to the search, it may provide a dramatic improvement in coverage of orbital parameter space for radio pulsars with binary characteristics akin to X1820–303.

Finally, in Table 7 we also summarize the results of simulations carried out to test the efficiency of our code at detecting a putative relativistic binary double-neutron star system in a highly eccentric short-period orbit (cases 5 and 6). As would be expected, for certain orbital phases a normal search has no hope of detecting such systems, while the acceleration search maintains a detection efficiency of at least 20% at all orbital phases. Our search would therefore have found a relatively bright relativistic binary pulsar in 47 Tuc at any orbital phase, but none was detected. This provides some empirical evidence that the population of pulsars in the central regions of 47 Tuc is composed exclusively of bona fide millisecond pulsars: those with rotation periods under ~ 10 ms, and in relatively circular orbits with low-mass companions, or with no companions at all.

5.1.2. Other Selection Effects

An interesting issue from the point of view of the origin and evolution of the pulsars in 47 Tuc is their intrinsic pulse period distribution. The observed distribution shown in Figure 4 spans a remarkably narrow range and suggests that there may be a deficit of pulsars below 2 ms. This interpretation should be viewed with some caution, however, given the small number statistics, and it is clear from Figure 2 that we begin to lose sensitivity to pulsars with $P \lesssim 2$ ms. Presently, therefore, the observations do not unambiguously address the question of what the shortest pulsar periods might be. Pulsar 47 Tuc W, for example, was originally detected at a period of 1.18 ms, showing that we are sensitive to some rather short periods, but to be truly

sensitive to $P \lesssim 1$ ms, a different experiment with higher time and frequency resolution will have to be carried out.

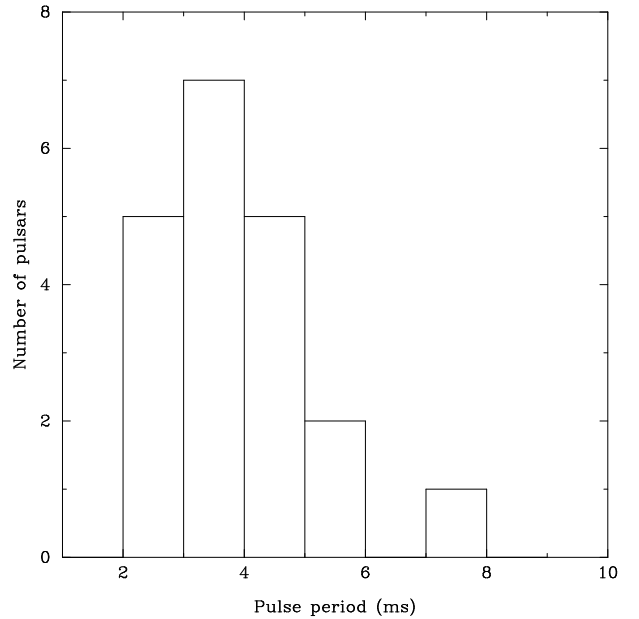


FIG. 4.— The observed period distribution of the 20 pulsars known in 47 Tuc. It is presently unclear to what extent the apparent deficit of pulsars with periods below 2 ms is a result of period-dependent selection effects (see §5.1.2).

It is likely that the vast majority of all pulsars in 47 Tuc are to be found within the area covered by the $14'$ -wide 20 cm telescope beam pattern. This is in keeping with expectations based on the radial density profile of 47 Tuc (De Marchi et al. 1996) from which we infer that almost 70% of the stars within the tidal radius of the cluster (Table 1) fall within the telescope beam area. This is additionally suggested by the observation that the pulsars for which a timing solution has been obtained are all located within a region with linear size $\sim 2'$, and that we have re-detected all pulsars discovered at lower frequencies, even though the area subtended on the sky by the 20 cm beam pattern is at most one-sixth that within which the first 11 pulsars were found. Nevertheless it is possible that some pulsars have been ejected from the central regions of the cluster, as is thought to be the case for M15 (Phinney & Sigurdsson 1991), and efforts to widen the search region might prove instructive.

There are a number of additional selection effects having to do with the manner in which we have reduced the data so far.

For isolated pulsars, the sensitivity limits might be improved by a factor of up to $\sim \sqrt{16}$ by reducing the entire 4.66 h data sets in a coherent manner. This could be done at reasonable computing expense because only the trivial zero-acceleration case would have to be addressed (once the Earth's rotation is accounted for). However, since flux densities for pulsars in 47 Tuc certainly vary significantly due to scintillation on time-scales of hours or less, the gain in sensitivity might be quenched by periods within the 4.66 h during which we would be adding mostly noise to the time series being analyzed. In extreme cases, the sensitivity could actually be degraded! Optimally then, each session's data stream should be analyzed with a multiplicity of integration spans. This can, however, degenerate into a huge overall data reduction task. These considerations also apply to the case of binary pulsars, where the additional need to perform sensitive acceleration searches over longer time intervals further exacerbates the overall computing load.

Finally, as already noted, we have analyzed most of the data at only one value of DM. The DMs for known pulsars in 47 Tuc span about one unit (Table 3), and this already introduces some loss of signal for the shortest period pulsars we have considered (§3). It would also be advantageous to broaden the range of DM searches because greater variance in the value of measured DMs might add to the understanding of the properties of the ionized intra-cluster, and interstellar, medium. Most of the variance observed for DMs of pulsars in globular clusters is expected to be due to slightly different lines-of-sight across the Galaxy, because most clusters are believed to be evacuated of gas (Spergel 1991).

5.2. Isolated Pulsars in 47 Tuc

Mindful of the comments in the previous section, we can still make some general statements about the likely intrinsic population of pulsars in 47 Tuc. The observed population of pulsars, all with millisecond periods, divides at present roughly into one-third isolated pulsars, one-third normal binary systems ($P_b \sim 0.4\text{--}2.3$ d and $m_2 \sim 0.2 M_\odot$), and one-third short-period binary systems ($P_b \sim 0.06\text{--}0.2$ d and $m_2 \sim 0.03 M_\odot$).

As mentioned previously, the fraction of isolated pulsars known in 47 Tuc prior to this survey was 64% of the total. Use of acceleration code has improved the detectability of binary systems, but we are still selecting severely against binaries of the short-period variety, when compared to isolated pulsars, and we consider it probable that the actual fraction of isolated pulsars in 47 Tuc is less than the 35% found at present. By comparison, the fraction of isolated millisecond pulsars in the disk of the Galaxy is $\sim 20\%$ (e.g., Camilo 1999). The surveys of the Galactic disk, because of their short integration times, are relatively more sensitive to short-period binaries, so the isolated fraction for disk pulsars, up to small-number statistics, is already known with some confidence.

The overall small fraction of isolated millisecond pulsars in 47 Tuc suggests an interesting puzzle: long-period binaries ($P_b \sim 10\text{--}10^3$ d) are expected to be formed at high rates in dense clusters through exchange interactions between old isolated neutron stars and “hard” primordial binaries (Hut et al. 1992; Sigurdsson & Phinney 1993). The long-period binaries have, however, high cross-section to disruption, and should eventually leave behind isolated millisecond pulsars. We detect no long-period binaries, and relatively few isolated pulsars. Perhaps most wide binaries are disrupted before the neutron star

companions can evolve into red giants, followed by mass transfer and birth of millisecond pulsars, as in the standard scenario (e.g., Verbunt 1993). This is an open question. In any case, even if the isolated fraction of millisecond pulsars in 47 Tuc and in the Galactic disk are comparable it is surely a coincidence, given the different evolutionary pressures present in both environments.

5.3. Profile Morphology

Chen & Ruderman (1993) suggested that the formation mechanism for millisecond pulsars in the Galactic disk and in globular clusters might be different. The observational evidence to support this idea relied on supposed differences in the observed radio beams (and hence magnetic field geometry, and origin) when comparing the collection of pulse profiles then available for disk millisecond pulsars and those in 47 Tuc, and in particular the supposed dearth of interpulses among the pulsars in 47 Tuc. More recently, Jayawardhana & Grindlay (1996) also presented evidence suggesting that the observed pulse width distribution of disk and cluster millisecond pulsars may be different.

Our collection of profiles for pulsars in 47 Tuc, shown in Figure 5, is larger and of higher quality than that presented by Manchester et al. (1991), on which Chen & Ruderman (1993) and Jayawardhana & Grindlay (1996) based their conclusions. In addition, there are now many more high-quality pulse profiles available for disk millisecond pulsars (Kramer et al. 1998; Stairs, Thorsett, & Camilo 1999). Given these observational improvements, it is appropriate to briefly review the situation regarding possible morphological differences. In an attempt to ensure homogeneity, we choose to compare our 20 cm profiles with the sample of 19 Galactic disk pulsars reported by Kramer et al. (1998) which were also obtained from 20 cm observations.

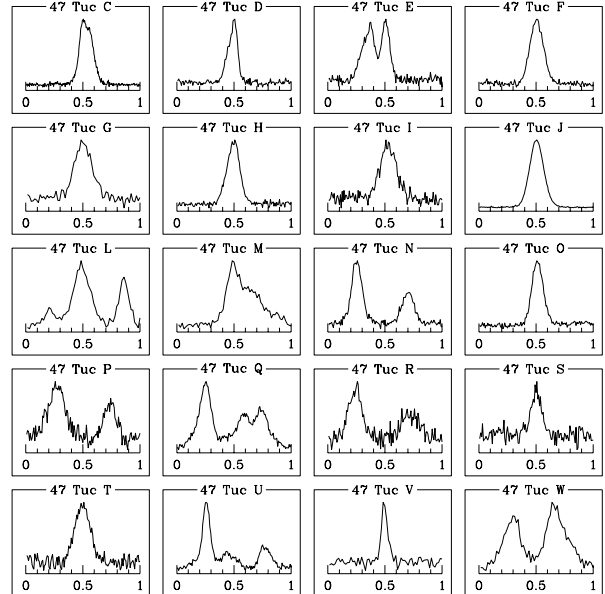


FIG. 5.— Average pulse profiles at 20 cm for pulsars in 47 Tucanae as a function of rotational phase. These profiles are available in digital form at the European Pulsar Network data archive (<http://www.mpifr-bonn.mpg.de/div/pulsar/data>). The effective time resolution for all profiles displayed is ~ 0.3 ms, ranging from 0.04 in pulse phase for 47 Tuc T to 0.14 for 47 Tuc J. Some profiles are not resolved (see Table 3).

In order to test the suggestion that the pulse widths of the pulsars in 47 Tuc are broader than their counterparts in the Galac-

tic disk, we compared the pulse width distribution measured at the 50% intensity level (w_{50}) for the 20 pulsars listed in Table 3 with that of the 19 disk millisecond pulsars presented in Table 2 of Kramer et al. (1998). A Kolmogorov-Smirnoff test returns a 25% probability that the two samples are drawn from the same underlying distribution. At best this is a marginally significant result, reflecting the larger fraction of Galactic disk millisecond pulsars for which $w_{50} < 10\%$ (but note that in spite of the improved time resolution of the new data, not all the profiles shown in Figure 5 are fully resolved).

Finally, from Figure 5 we note that 11 pulsars have essentially simple, single-component profiles; five pulsars have clear interpulses; and four more have profiles that may be described as complex, with emission evident across much of the period or in several distinct components. Inspecting the sample of Galactic disk millisecond pulsars presented by Kramer et al. (1998), we find five clear interpulses from a sample of 24 pulsars. Given the present statistics, this is entirely consistent with the fraction of interpulses we observe in 47 Tuc, refuting the morphological differences suggested by Chen & Ruderman (1993).

5.4. Eclipsing Pulsars

Robinson et al. (1995) show that, at 70 and 50 cm, 47 Tuc J is eclipsed by its companion for about a quarter of its orbit. We find that at 20 cm, on the other hand, the pulsar is always visible at all orbital phases. However 47 Tuc O, a pulsar system in many respects similar to 47 Tuc J, is always eclipsed for about 10–15% of its orbit at 20 cm.

There are three other similar systems known in 47 Tuc, with orbital periods of less than 6 h and with $\sim 0.03 M_{\odot}$ companions. 47 Tuc P and R were detected at only one epoch, although at least one full orbit was covered in each case: 47 Tuc P was seen at all orbital phases, while 47 Tuc R was apparently eclipsed for $\sim 25\%$ of its orbit, centered with the pulsar at superior conjunction (Fig. 3). 47 Tuc I is detected much more often, and there are no eclipses observed at 20 cm.

Finally, 47 Tuc V also displays apparent eclipses, but we cannot yet characterize the system or its eclipses, which may be irregular (§4.2); and 47 Tuc W, with $m_2 \sim 0.15 M_{\odot}$, was eclipsed for $\sim 25\%$ of its orbit on the only occasion it was detected (Fig. 3). While based on orbital parameters we suggest that the system may be somewhat similar to the eclipsing pulsar B1744–24A in Terzan 5 (§4.2), we cannot yet be sure.

In the Galactic disk there are two pulsar systems known that have properties broadly similar to some of the above eclipsing pulsars. PSRs B1957+20 and J2051–0827 (Arzoumanian, Fruchter, & Taylor 1994; Stappers et al. 1996) are millisecond pulsars in very circular orbits with $\sim 0.03 M_{\odot}$ companions, with orbital periods of a few hours. These pulsars are both eclipsed by their companions, apparently bloated to fill their Roche lobes, but the systems differ in eclipse phenomenology: PSR B1957+20 always displays eclipses for $\sim 20\%$ of its orbit, at all frequencies, while PSR J2051–0827 is eclipsed at low radio frequencies, but is visible at all orbital phases at 20 cm; in the latter instance, however, the radio pulses suffer extra time delays as they propagate in a dispersive medium. The differences observed in these systems are likely due to a combination of different masses and chemical compositions of the companions, and possibly evolutionary states; the energy that is deposited at the companion by the relativistic pulsar wind, which in turn depends on the pulsar spin parameters, beaming geometry, and orbital separation; and geometrical effects. It is not yet clear if the eclipse behavior for 47 Tuc J or O, let alone that

for the seldom-detected pulsars in 47 Tuc, is similar to that of either PSR J2051–0827 or B1957+20.

5.5. The Central Mass Density of 47 Tuc

In Table 4 we list phase-connected timing solutions for three pulsars. An unusual feature of all the solutions is that the period derivatives, \dot{P} , are negative, apparently implying the pulsars are spinning up, rather than spinning down as is the case for all pulsars known in the Galactic disk, which are losing rotational energy emitted in the form of magnetic dipole radiation and a relativistic particle wind. In fact this is a feature observed in some other globular cluster pulsars (see, e.g., Wolszczan et al. 1989), and is most easily interpreted by considering that the observed \dot{P}_{obs} is a combination of the intrinsic $\dot{P}_{\text{int}} (\geq 0)$ and a contribution resulting from the acceleration of the pulsar in the gravitational potential of the cluster, such that

$$\dot{P}_{\text{obs}} = \dot{P}_{\text{int}} + \dot{P}_{\text{acc}}. \quad (6)$$

In this equation, $\dot{P}_{\text{acc}}/P = a_l/c$, where a_l is the acceleration along the line of sight (Phinney 1992). A negative \dot{P}_{obs} implies the pulsar lies behind the cluster center as seen from the Sun.

Given a model for the mass distribution in the cluster, a lower limit on a_l by assuming $\dot{P}_{\text{int}} = 0$, and an accurate pulsar position, one can estimate a lower limit to the central mass density in the cluster. Assuming that the central regions of the cluster can be described by King’s (1962) empirical density model, one obtains for the central central mass density

$$\rho(0) > \left| \frac{a_l r}{4\pi G \kappa^2} \right| = \left| \frac{9cr\dot{P}}{4\pi G r_c^2 P} \right|. \quad (7)$$

In this expression r is the projected distance of the pulsar from the cluster center and κ is the Jeans length at the cluster center. For a King model, we have made the standard approximation that κ is one third of the core radius of the cluster, r_c . We use equation 7 for the pulsars in 47 Tuc by taking the most recent and reliable determination of the angular core radius, based on a fit of a King radial density profile to the observed stellar population; together with a distance estimate to 47 Tuc (Table 1), equation 7 becomes

$$\rho(0) > 2.8 \times 10^5 \left(\frac{R}{\text{arcmin}} \right) \times \left(\frac{\dot{P}_{\text{acc}}}{10^{-20}} \right) \times \left(\frac{P}{\text{ms}} \right)^{-1} M_{\odot} \text{pc}^{-3}. \quad (8)$$

Here R is the angular separation between the pulsar and the center of the cluster (see Table 1). Using the celestial coordinates, P , and \dot{P} , listed in Table 4 for 47 Tuc C, D, and J, we obtain from equation 8 lower limits on $\rho(0)$ of, respectively, 30, 1, and $13 \times 10^4 M_{\odot} \text{pc}^{-3}$.

The most stringent lower limit on $\rho(0)$, which we obtain from the position and period derivative of 47 Tuc C, is some four times larger than the value quoted by Robinson et al. (1995) for the same pulsar. This is due to our use of the latest core radius estimate (De Marchi et al. 1996) which is approximately half the value of previous estimates (see, e.g., Calzetti et al. 1993). De Marchi et al. demonstrate that the difference in core radius estimates can be entirely attributed to the effects of photometric incompleteness in the earlier samples.

If a King model can be used to describe the central regions of the cluster, and the observations of De Marchi et al. (1996) suggest that this is the case, the above are hard limits on $\rho(0)$, due

to the assumption so far that $\dot{P}_{\text{int}} = 0$. In fact \dot{P}_{int} is likely to have some finite positive value, such that we have thus far underestimated the accelerations felt by the pulsars. We now present some plausibility arguments that lead in general to more realistic estimates of a limit on $\rho(0)$.

Most millisecond pulsars known in the Galactic disk ($1.5 < P < 9$ ms) have inferred intrinsic surface dipole magnetic field strengths of 10^8 – 10^9 G, with an average of $B \sim 3 \times 10^8$ G (e.g., Camilo, Thorsett, & Kulkarni 1994). For a given P and B , the period derivative is obtained (e.g., Manchester & Taylor 1977) from

$$\dot{P} = 10^{-19} \left(\frac{P}{\text{ms}} \right)^{-1} \times \left(\frac{B}{3.2 \times 10^8 \text{ G}} \right)^2. \quad (9)$$

We have no *a priori* information about the magnetic field strengths of the pulsars in 47 Tuc, but if they were significantly higher than those for disk pulsars, so would the respective \dot{P} . For a putative 6 ms pulsar, like 47 Tuc C, but with $B = 10^{10}$ G, we obtain $\dot{P} = 2 \times 10^{-17}$ from equation 9. In turn, when used with equation 8, this would imply $\rho(0) > 3 \times 10^7 M_\odot \text{ pc}^{-3}$, an unreasonably large value! A similar argument can be made for 47 Tuc J. If the magnetic fields of the millisecond pulsars in 47 Tuc are not likely to be much larger than those of millisecond pulsars in the disk, we may assume that they are, on average, comparable.

Following the above arguments, we calculate from equation 9 the likely values of \dot{P}_{int} for 47 Tuc C and J: 1.7×10^{-20} and 4.8×10^{-20} respectively, for $B = 3.2 \times 10^8$ G. These expected values can be decreased or increased by a factor of ten, considering the entire range $10^8 < B < 10^9$ G. To be conservative, we consider only $10^8 < B < 3.2 \times 10^8$ G. For 47 Tuc C, the full contribution due to acceleration in the cluster (from eq. 6), is 5.1 – 6.7×10^{-20} , while for 47 Tuc J it is 1.4 – 5.7×10^{-20} . These contributions are increased over the hard limits assuming $\dot{P}_{\text{int}} = 0$ by factors of 1.0–1.3 for 47 Tuc C and 1.5–6.1 for 47 Tuc J. Finally, the implied lower limits on $\rho(0)$ are increased to 3 – $4 \times 10^5 M_\odot \text{ pc}^{-3}$ and 2 – $10 \times 10^5 M_\odot \text{ pc}^{-3}$, for 47 Tuc C and J respectively.

We conclude from the present timing solutions that $\rho(0) > 3 \times 10^5 M_\odot \text{ pc}^{-3}$. This lower limit can be compared to “standard estimations” of $\rho(0)$, based on optical measurements of King model parameters (e.g., Webbink 1985). The aforementioned revision in the core radius value for 47 Tuc implies that the existing estimate for $\rho(0)$, which scales as r_c^{-2} (King 1966; Spitzer 1987), should be revised appropriately. Scaling the value for $\rho(0)$ tabulated by Webbink (1985), we find $\rho(0) = 4 \times 10^5 M_\odot \text{ pc}^{-3}$. While this is in agreement with our present lower limits, it is unlikely that both 47 Tuc C and J have the lowest magnetic field strengths of any known pulsars and so, in the context of a King model, the above discussion is strongly suggestive that for 47 Tuc, $\rho(0) > 4 \times 10^5 M_\odot \text{ pc}^{-3}$, and possibly is as much as a factor of two or so larger.

5.6. Pulsar Luminosities

Except for 47 Tuc C, D, and J, pulsars in 47 Tuc are detected on fewer than 75% of observing days, and we have detected some of the pulsars on only one of 75 observing days (see Tables 2 and 6). Given this fact, it is not appropriate to estimate average flux densities for most pulsars by simply averaging the detected signal-to-noise ratios and converting to flux densities using the approximately known system noise and detection apparatus characteristics. In this section we present a more rigorous method to estimate mean flux densities of the pulsars in

47 Tuc.

The variability in apparent flux densities, apart from the occurrence of eclipses, results from interstellar scintillation (Rickett 1977), and we proceed further by assuming that scintillation affects all pulsars in 47 Tuc similarly, since they are all located in relatively close proximity.

Given this assumption, we construct cumulative histograms in $\log(\sigma)$ for the frequently-detected pulsars in the cluster, and attempt to synthesize a “standard” histogram which we take to be representative of the relative flux variations due to interstellar scintillation for a pulsar in 47 Tuc. Initially the standard histogram is defined to be that of 47 Tuc J, the brightest pulsar. The histograms of other frequently-appearing pulsars are then shifted by a scaling factor in a fitting procedure so as to match the standard as closely as possible, in a least-squares sense. A new standard is then defined where σ of the n^{th} strongest “observation” is the average of the respective values from each of the individually shifted histograms, and this procedure is iterated until the scaling factors are stationary and a self-consistent solution is obtained. The scaling factors with respect to the final standard (see Fig. 6) therefore provide an estimate of the average relative signal-to-noise ratios of the various pulsars.

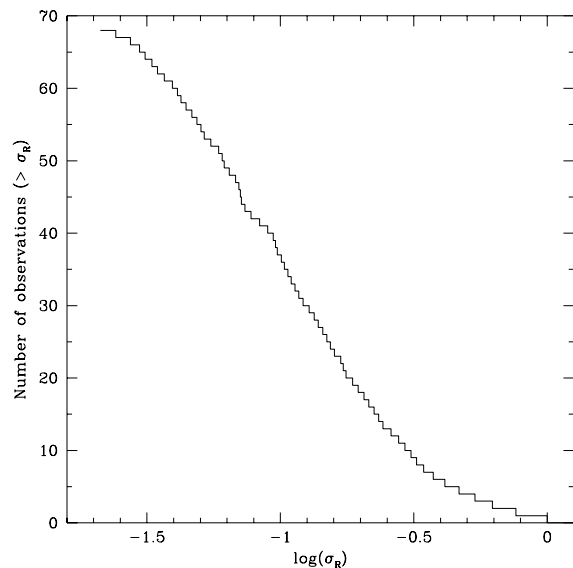


FIG. 6.— Cumulative “standard” histogram of $\log(\sigma_R)$ for observations of pulsars in 47 Tuc. σ_R is the signal-to-noise ratio of an “observation”, σ , scaled to the maximum signal-to-noise ratio, σ_{max} , i.e., $\sigma_R = \sigma/\sigma_{\text{max}}$. See §5.6 for details.

For 47 Tuc J we obtain the actual average σ from the observations (Table 2), but correct it downwards to take into account the $\sim 10\%$ of observing days in which we do not detect the pulsar. We do this by assuming that on these days, on average, the pulsar has a flux density that is half of the lowest value detected, resulting in a 10% correction. After applying the scaling factors and converting to a flux density scale using the methodology outlined in §3, we obtain the average flux densities listed in Table 3 for 14 pulsars.

One obvious problem with this method is that for the less-frequently appearing pulsars only part of the cumulative histogram is being fitted to — and to the extent that the standard histogram is in fact not precisely descriptive of the scintillation behavior of all pulsars, this may particularly skew the average σ for such pulsars. We have accounted for this in the uncertainties

listed in Table 3. In addition, until we calibrate the sensitivity of the observing system with a pulsed source of known strength, the conversion between σ and flux density is subject to a systematic uncertainty that we judge to be of the order of $\sim 25\%$.

Pulsars 47 Tuc C, D, and J, for which we have the most reliable flux density estimates, display maximum “daily” flux densities that are factors of 4–8 greater than the average values. This is the only information we have available that is of some use to estimate, very roughly, the average flux density for the pulsars that are detected very infrequently (Table 6). We obtain estimates of ~ 0.04 mJy for the average flux density of these pulsars. We note this plausible estimate simply to suggest that the flux densities of these pulsars need not be much lower than those of the weakest among the more frequently-appearing pulsars.

The weakest pulsars we have been able to detect in 47 Tuc have flux densities at 1400 MHz of about $S_{1400} = 0.04$ mJy, while the strongest, 47 Tuc J, has $S_{1400} = 0.54$ mJy. At the distance of 47 Tuc (Table 1), these correspond to luminosities at 1400 MHz, $L_{1400} \equiv S_{1400} d^2$, of 0.8–11 mJy kpc². Translated to luminosities at frequencies ~ 400 MHz, assuming a spectral index for the pulsars in 47 Tuc of -2.0 , these correspond roughly to $10 < L_{400} < 130$ mJy kpc².

The limiting minimum luminosity for Galactic disk pulsars at ~ 400 MHz is about 1 mJy kpc² or lower (Lorimer et al. 1993; Lyne et al. 1998). For the Galactic disk (Lyne, Manchester, & Taylor 1985) and M15 (Anderson 1992), the differential luminosity distribution for pulsars is found to be consistent with $dN = L^{-1} d \log L$. Assuming that these findings apply to 47 Tuc, we estimate there are about 10 times as many potentially observable pulsars in the luminosity decade 1–10 mJy kpc² as there are in 10–100 mJy kpc², where we already know of about 20 pulsars. Hence we estimate a potentially observable popula-

tion of pulsars in 47 Tuc, similar to the ones already detected, of about 200, above a minimum luminosity $L_{400} \sim 1$ mJy kpc². When beaming and selection effects are accounted for we judge it likely that 47 Tuc contains several hundred pulsars with $L_{400} \gtrsim 1$ mJy kpc².

The actual determination of the luminosity distribution, and a detailed discussion of flux densities, spectral indices, and scintillation properties for the pulsars in 47 Tuc, will rely on more complete multi-wavelength data sets, and will be addressed elsewhere. It is already clear however, that we have detected only the few brightest pulsars in 47 Tuc, and continued searches of this cluster, particularly with greater sensitivity, should yield a bounty of new discoveries.

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